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TECHNICAL NOTE

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AERODYNAMIC-HEATING DATA OBTAINED FROM FREE-FLIGHT TESTS BETWEEN MACH NUMBERS OF 1 AND 5[1]

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SUMMARY

Two rocket-propelled models have been flown to Mach numbers of 5.0 and 5.6. Aerodynamic-heating data were obtained from temperature measurements made at a single station on each model. In the case of model 1, data were obtained on the parabolic nose between free-stream Mach numbers of 2.3 and 5.0. The local Mach number, which is the Mach number of the airstream just outside the boundary layer at the measuring station, varied from 2.1 to 4.5; these values corresponded to local Reynolds numbers of 11×10^6 to 19×10^6. The ratio of skin temperature to local static temperature varied from 1.1 to 2.6. The experimental data when reduced to Stanton numbers were in fair agreement with values predicted by Van Driest's theory for heat transfer on a cone with turbulent flow from the nose tip.

Aerodynamic-heating data were obtained on the conical nose of model 2 between Mach numbers 1.1 and 4.0. The local Mach numbers varied from 1.0 to 3.8; these values corresponded to local Reynolds numbers from 14×10^6 to 28×10^6. The ratio of skin temperature to local static temperature varied from 1.0 to 2.3. Over most of the test range, the data were in fair agreement with Van Driest's theory for turbulent flow on a cone.

INTRODUCTION

The Langley Pilotless Aircraft Research Division has initiated a program to develop its rocket test technique to enable free-flight testing at Mach numbers well into the hypersonic range. This program is the result of an obvious need for data in this Mach number range for use in the development and evaluation of theory and in the design of missiles and airplanes.

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[1]Supersedes recently declassified NACA Research Memorandum L55A14a by Charles B. Rumsey, Robert O. Piland, and Russell N. Hopko, 1955.

As an initial step in this program, two exploratory models have been flight tested to Mach numbers of 5.0 and 5.6, respectively. The primary purpose of these tests was to obtain information to guide the design of future higher speed models. In each model, therefore, a single temperature pickup was installed on the nose skin of the model. In each flight the skin-temperature instrument failed at or prior to maximum flight Mach number and before maximum skin temperature had been reached. However, the limited amount of data obtained is believed to be of interest because of the scarcity of heat-transfer data at the high stagnation temperatures and Reynolds numbers corresponding to free flight at these Mach numbers and is consequently presented herein.

During the flight of model 1, the skin-temperature instrument failed at the peak Mach number of 5.0 with a maximum recorded temperature of 920° F. Aerodynamic-heat-transfer data were obtained on the parabolic nose of this model over the free-stream Mach number range from 2.3 to 5.0. The local Mach number, which is the Mach number of the airstream just outside the boundary layer at the measurement station, varied from 2.1 to 4.5; these values corresponded to local Reynolds numbers of 11×10^6 to 19×10^6. The ratio of skin temperature to local static temperature varied from 1.1 to 2.6.

Model 2 reached a peak Mach number of 5.6 but the skin-temperature instrument failed when the model reached a Mach number of 4. Aerodynamic-heat-transfer measurements were obtained on the conical nose of this model over a free-stream Mach number range from 1.1 to 4.0. The local Mach number varied from 1.0 to 3.8; these values corresponded to local Reynolds numbers from 14×10^6 to 28×10^6. The ratio of skin temperature to local static temperature varied from 1.0 to 2.3.

The flight tests were conducted at the Langley Pilotless Aircraft Research Station at Wallops Island, Va.

SYMBOLS

A	area, sq ft
c_p	specific heat of air at constant pressure, Btu/slug-°F
c_w	specific heat of wall material, Btu/lb-°F
h	local aerodynamic-heat-transfer coefficient, Btu/sec-sq ft-°F
k	thermal conductivity of air, Btu-ft/sec-°F-sq ft

l	axial distance from nose to skin-temperature measurement station, ft
M	Mach number
Q	quantity of heat, Btu
$\frac{dQ_{RC}}{dt}$	rate of heat flow due to radiation and conduction along the skin, Btu/sec
R.F.	recovery factor, $\frac{T_{aw} - T_v}{T_{so} - T_v}$
T	temperature, $^{\circ}F$
t	time, sec from start of flight
V	velocity, ft/sec
γ	ratio of specific heats
μ	viscosity of air, slugs/ft-sec
ρ	density of air, slugs/cu ft
ρ_w	density of wall material, lb/cu ft
τ	thickness of wall, ft
C_H	Stanton number, $h/C_p\rho_vV_v$
Pr	Prandtl number, $C_p\mu/k$
R	Reynolds number, $\rho Vl/\mu$

Subscripts:

aw	adiabatic wall
o	undisturbed free stream ahead of model
so	stagnation
v	just outside boundary layer at measurement station
w	wall

MODELS AND TESTS

General.- The two rocket-propelled models were launched from the ground at elevation angles of about 70°. Each model employed a two-stage propulsion system consisting of a booster which drag-separated at burnout and a sustainer motor which ignited at a predetermined time after booster separation. Maximum Mach number occurred at sustainer burnout.

The tests reported herein consisted of measurements of aerodynamic heat transfer made at a single station on the nose of each model. The resistance-type skin-temperature pickups consisted of a platinum wire $\left(0.0005 \text{ inch in diameter approximately } 1\frac{1}{2} \text{ inches long}\right)$ cemented to the inside surface of the nose skin. Resistance of the wire was calibrated against skin temperature. The development, construction, and accuracy of the instrument are described in reference 1.

Each model carried a four-channel telemeter which transmitted the information from the skin-temperature pickup and from three other instruments not related to the heat-transfer tests. Velocity and altitude data were measured by means of CW Doppler radar and SCR-584 tracking radar, respectively. Atmospheric conditions were measured by means of the SCR-584 radar data in conjunction with radiosondes launched near the time of flight.

Model 1.- A drawing and a photograph of model 1 are shown in figures 1(a) and 1(b), respectively. The nose shape which was parabolic back to station 24 was a 2/3-scale replica of the NACA RM-10 parabolic body (ref. 2). A modification was made to the nose tip as shown in figure 1(a) to allow measurement of total pressure (not associated with the heat-transfer tests). Except for this 0.05-inch-diameter hole, the nose tip was constructed of solid steel and was welded to the skin at station 2. The Inconel skin which was approximately 0.031 inch thick had no attachments which would contribute to the thermal capacity of the skin back to station 27.8. The temperature pickup was attached to the interior surface of the skin at station 8.5. The exterior surface of the nose skin was highly polished.

The telemeter was located in the nose section and had asbestos wrappings that provided some protection from the high skin temperatures. Back of the nose section the body consisted of an HPAG 5-inch-diameter rocket motor with four stabilizing fins welded to the nozzle.

The model was boosted by three 6.25-inch ABL Deacon rocket motors to a Mach number of 2.5. After a coasting period of 0.5 second, the HPAG sustainer motor fired and accelerated the model to a maximum Mach number of 5.0. Figure 2 presents time histories of Mach number, altitude, and skin temperature from 2.5 to 6.5 seconds, with the exception of an interval between 3 and 3.8 seconds during which time no velocity data were obtained. The skin temperature pickup failed abruptly at 6.5 seconds.

Model 2.- A drawing and photograph of model 2 are shown in figures 3(a) and 3(b), respectively. The configuration consisted of a 10° total angle conical nose and a cylindrical body with four stabilizing fins mounted around the base. The conical nose on which the skin-temperature measurements were made was 40 inches long and was constructed of Inconel skin approximately 0.029 inch thick except for the forward end which was made of steel, hollowed out as shown in figure 3(a), and welded to the skin at station 6. Back to station 28, there were no attachments to the skin which would contribute to the thermal capacity of the skin. The skin-temperature pickup was attached to the inner surface of the skin at station 22.5. The exterior surface of the nose skin was highly polished and had a surface roughness of approximately 5 microinches root mean square as measured by a Physicists Research Co. Profilometer.

The telemeter was located in the nose section and was protected from the high skin temperatures by a radiation shield which consisted of a second Inconel cone spaced approximately 1/4 inch inside the exterior skin. The Deacon sustainer motor was carried inside the rolled-steel cylindrical body.

Figure 3(c) is a photograph of the model and its booster in launching position. The 2.5-DS-59000 booster rocket accelerated the model to a Mach number of 2.9. After a coasting period of 5.7 seconds, the Deacon sustainer motor fired and accelerated the model to a maximum Mach number of 5.6. Figure 4 shows time histories of Mach number, altitude, and skin temperature from takeoff to 12.0 seconds at which time the skin-temperature pickup failed. The trend of the skin-temperature measurements just before 12 seconds shows that the failure was progressive. The heat-transfer coefficients obtained from the measurements and discussed later tend to indicate that the failure began at about 10.6 seconds.

ACCURACY

The probable error in the skin-temperature measurements used in obtaining the heat-transfer data is within ±2 percent of the full-scale range of the instrument. This error results in a maximum probable error in T_w/T_v of ±4 percent at maximum measured temperature for model 1. For model 2, the maximum probable error in T_w/T_v is ±5 percent at maximum measured temperature. The maximum probable error in Reynolds number for either model is believed to be within ±2 percent and Mach number measurements are accurate within ±0.01.

DATA REDUCTION

General.- The rate of heat exchange between the skin and boundary-layer air adjacent to it is proportional to the temperature difference and the heat-transfer coefficient. By neglecting radiation and conduction along the skin, which are considered later, the time rate of heat exchange between the boundary layer and skin may be written

$$\frac{dQ}{dt} = hA_w\left(T_{aw} - T_w\right) \tag{1}$$

and the time rate of change of heat contained in the skin is

$$\frac{dQ}{dt} = \rho_w C_w \tau A_w \frac{dT_w}{dt} \tag{2}$$

Equating equations (1) and (2) and solving for h gives

$$h = \frac{\tau \rho_w C_w}{T_{aw} - T_w} \frac{dT_w}{dt} \tag{3}$$

The thickness, density, and specific heat of the skin material were known. The values of specific heat used were taken from tests currently being performed by the National Bureau of Standards under a contract for the National Advisory Committee for Aeronautics. These tests show that the instantaneous specific heat of annealed Inconel of 0.07 percent carbon content varies with temperature in the range from 32° F to 930° F as shown in figure 5. Above 930° F there is indication of a specific heat anomaly. The values of skin temperature and rate of change of skin temperature with time required in equation (3) were obtained from the measured skin-temperature data. The remaining quantity, the adiabatic wall temperature, was obtained in the following manner from the relation:

$$\text{R.F.} = \frac{T_{aw} - T_v}{T_{so} - T_v}$$

For turbulent flow, the recovery factor is approximately equal to $Pr^{1/3}$ (ref. 3) where the skin temperature is the reference temperature. Therefore,

$$T_{aw} = Pr^{1/3}\left(T_{so} - T_v\right) + T_v$$

where

$$T_{so} = T_o \left(1 + \frac{\gamma - 1}{2} M_o^2\right)$$

and

$$T_v = \frac{T_{so}}{1 + \frac{\gamma - 1}{2} M_v^2}$$

The Mach number just outside the boundary layer M_v is found from the conical shock tables as a function of free-stream Mach number and cone angle.

In the case of model 1, the nose shape is parabolic; however, the change in surface slope from the tip back to the measuring station 8.5 is only 1°. Therefore, conical flow was assumed over the nose back to the measuring station by using a cone half-angle of 6.5° which is the surface slope at the temperature measuring station.

Stanton number is readily calculated after h has been determined since

$$C_H = \frac{h}{C_p \rho_v V_v}$$

The values for the specific heat of air at T_v were obtained from reference 4, values of V_v were computed from M_v and T_v, and values of ρ_v were determined from the conical shock tables and energy relations with the cone-angle and free-stream conditions known.

Model 1.- During the portion of the flight for which heat-transfer data are presented, the skin was being heated by the boundary layer. The rate of heating, varying from 125° F per second at 2.5 seconds to 285° F per second at 6 seconds, was large. Under these conditions, the effects of radiation are less than 1 percent of the aerodynamic heat transfer (eq. (1)) and are neglected in the reduction of the data for this model.

Model 2.- When the time rate of change of temperature at a point on the skin is zero, the rate of heat flow to the skin from the boundary layer (aerodynamic heating) is equal to the rate of heat loss at the point due to radiation and heat flow along the skin. This relation can be written

$$\frac{dQ}{dt} = hA_w\left(T_{aw} - T_w\right) + \frac{dQ_{RC}}{dt} = 0 \qquad (4)$$

and equation (3), modified to include the radiation and conduction term, becomes

$$h = \frac{\tau \rho_w A_w c_w \frac{dT_w}{dt} - \frac{dQ_{RC}}{dt}}{A_w\left(T_{aw} - T_w\right)} \tag{5}$$

The skin temperature against time curve for model 2 (see fig. 4) has a point of zero slope at 7.25 seconds. A value of h for the flight conditions occurring at 7.25 seconds was determined from Van Driest's theory for turbulent flow on a cone (ref. 5) and was then used in equation (4) to compute the value of $\frac{dQ_{RC}}{dt}$. This value was assumed to be constant during the time from 4.5 seconds to 10.5 seconds since the skin temperature was relatively constant during this interval. At times 5.5 and 9.5 seconds, this correction for radiation and conduction increased the values of C_H by approximately 20 percent while at 4.5 and 10.5 seconds it increased C_H by approximately 5 percent. Prior to 4.5 seconds and after 10.5 seconds, the correction was not employed since the skin temperature was different from the skin temperature at which the correction was determined. In addition, the rates of change of skin temperature were great enough to make the correction small relative to the determined values of C_H.

RESULTS AND DISCUSSION

The aerodynamic heating of a flat plate with turbulent boundary layer has been shown theoretically in reference 6 to be a function of Mach number, Reynolds number, and T_w/T_o, the ratio of skin temperature to free-stream temperature. In reference 5, the same relation is shown theoretically to apply to a cone when a modification is made to Reynolds number, and local conditions just outside the boundary layer are used in place of free-stream conditions. In the present tests the parameters Mach number, Reynolds number, and temperature ratio all vary and make it impossible to isolate their individual effects. The measured aerodynamic heat-transfer rate, as indicated by Stanton number, is therefore presented as a function of time in figures 6 and 7 for models 1 and 2, respectively. On the same figures, the variations of local Mach number, local Reynolds number based on length from the nose tip, and the ratio of skin temperature to local static temperature are also presented. The theory of Van Driest for a cone with turbulent boundary layer (ref. 5) has been used to estimate C_H through the flight by using the test values of M_v, R_v, and T_w/T_v; the results are compared in figures 6 and 7 with the measured values for models 1 and 2, respectively.

In the case of model 1 the experimental values of Stanton number are in fair agreement with the theory. The slightly higher than predicted values of Stanton number measured during the early part of the flight are probably due to a short run of laminar flow preceding the turbulent region which obviously exists at the temperature measuring station. The largest differences between measured and predicted values occur, however, at the time of highest Mach numbers. It is possible that the strong cooling of the boundary layer, that is, the increasing difference in adiabatic wall and skin temperature with time, is having a stabilizing effect on the laminar boundary layer with a resulting increase in Reynolds number of transition. If so, the rapid change in slope of Stanton number (at about 5 seconds) could indicate a transition region. No heat-transfer data were obtained between 3 and 3.8 seconds because, as stated earlier, no velocity data were obtained during this time.

Two points which were considered as possibly affecting the comparison between theory and experiment are the parabolic nose shape, as opposed to the conical shape assumed by theory, and the modification to the nose tip to allow measurement of total pressure. The former is not believed to affect the comparison greatly since the portion of the nose under consideration (to the pickup station) deviates only slightly from a constant slope. The effect of the latter is also believed to be small simply because the diameter of the tip is small. (See figure 1(a).)

As stated earlier, local conditions were used in reducing the temperature measurements to Stanton number. The measurements were also reduced by using free-stream conditions. For model 1 this change resulted in values of Stanton number 30 percent higher at the higher Mach numbers than those obtained using local conditions. The difference in Stanton number will be even greater at higher Mach numbers and with blunter nose shapes. It is apparent that large differences could result from using free-stream rather than local conditions in estimating skin temperatures from the theory of Van Driest.

The values of C_H for model 2 (fig. 7) are in fair agreement with Van Driest's theory for turbulent flow on a cone, except for the scatter in the data between 7.5 seconds and 9.5 seconds, and the trend of the data after 10.6 seconds. It is noted that, during the interval from 7.5 seconds to 9.5 seconds, the values of temperature potential $T_{aw} - T_w$ and the skin heating rate dT_w/dt are at or near zero. Examination of equation(5) shows that, under such temperature conditions, relatively small uncertainties in the measured data may result in considerable scatter in the C_H values.

After 10.6 seconds, the experimental values of C_H decrease sharply. However, as noted previously, the temperature pickup failed completely at

12 seconds and the failure seems likely to have been progressive from 10.6 seconds on in view of the trend of the data.

CONCLUDING REMARKS

Two rocket-propelled models have been flown to Mach numbers of 5.0 and 5.6. Aerodynamic-heating data were obtained from temperature measurements made at a single station on each model. In the case of model 1, data were obtained on the parabolic nose between free-stream Mach numbers of 2.3 and 5.0. The local Mach number, which is the Mach number of the airstream just outside of the boundary layer at the measuring station, varied from 2.1 to 4.5; these values corresponded to local Reynolds numbers of 11×10^6 to 19×10^6. The ratio of skin temperature to local static temperature varied from 1.1 to 2.6. The experimental data when reduced to Stanton number were in fair agreement with values predicted by Van Driest's theory for heat transfer on a cone with turbulent flow from the nose tip.

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Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., December 30, 1954.

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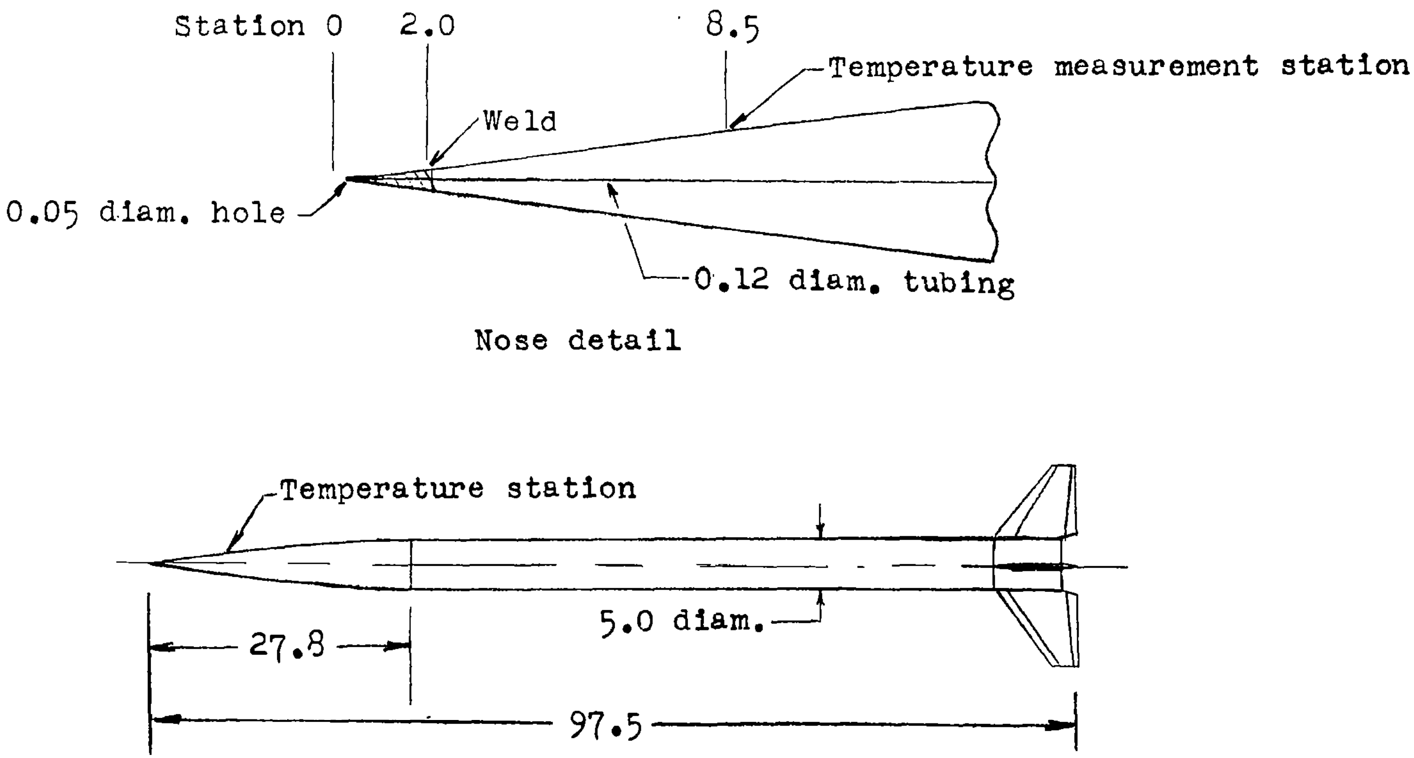
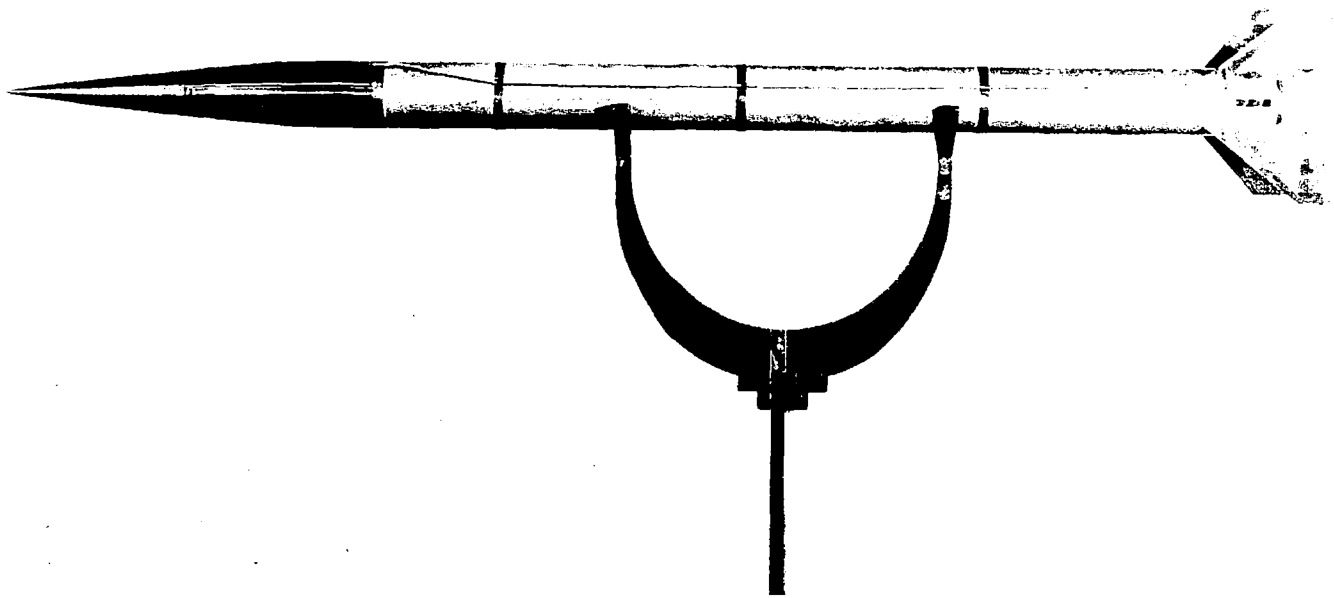


(a) General configuration. Dimensions are in inches.

Figure 1.- Model 1.



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(b) Photograph of model 1.

Figure 1.- Concluded.

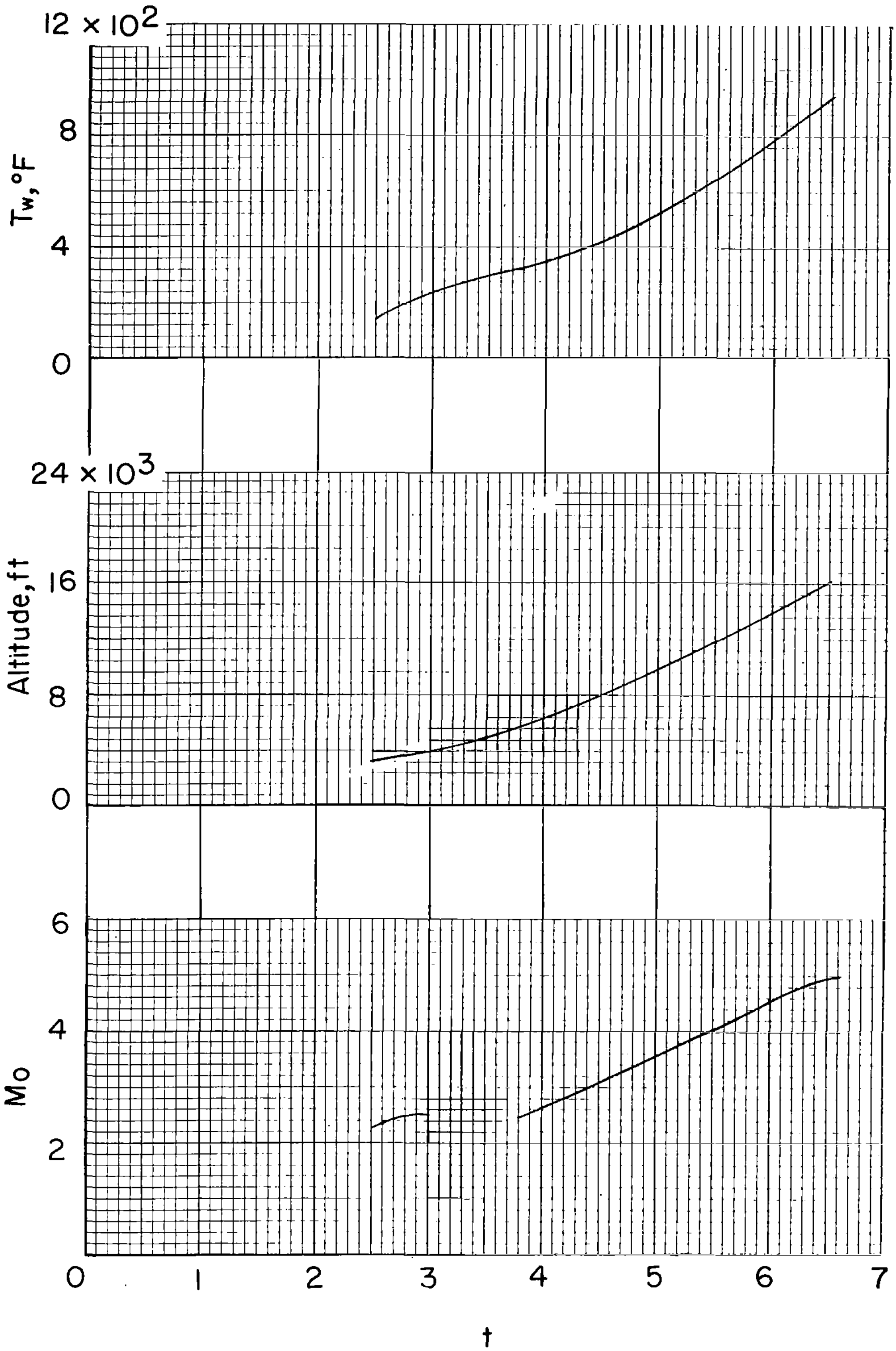
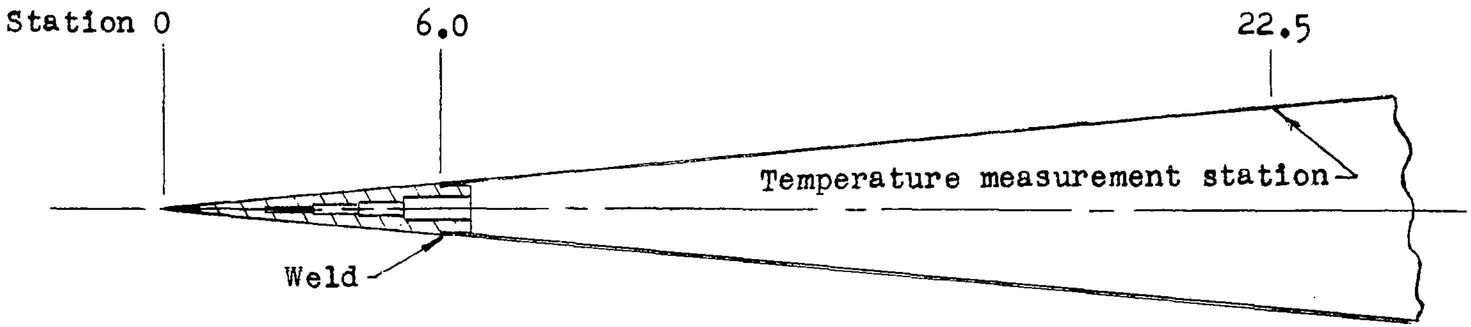
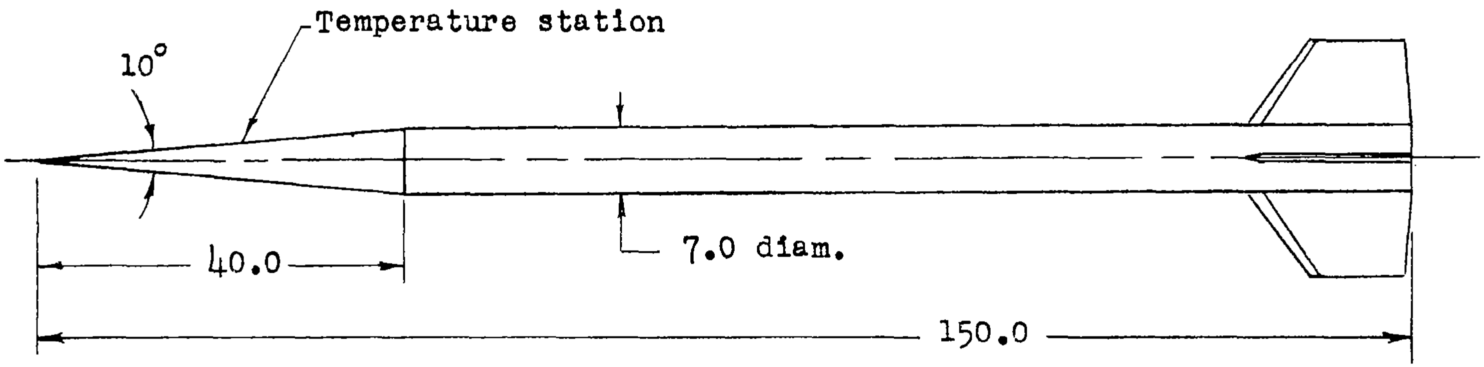


Figure 2.- Time histories of flight conditions for model 1.

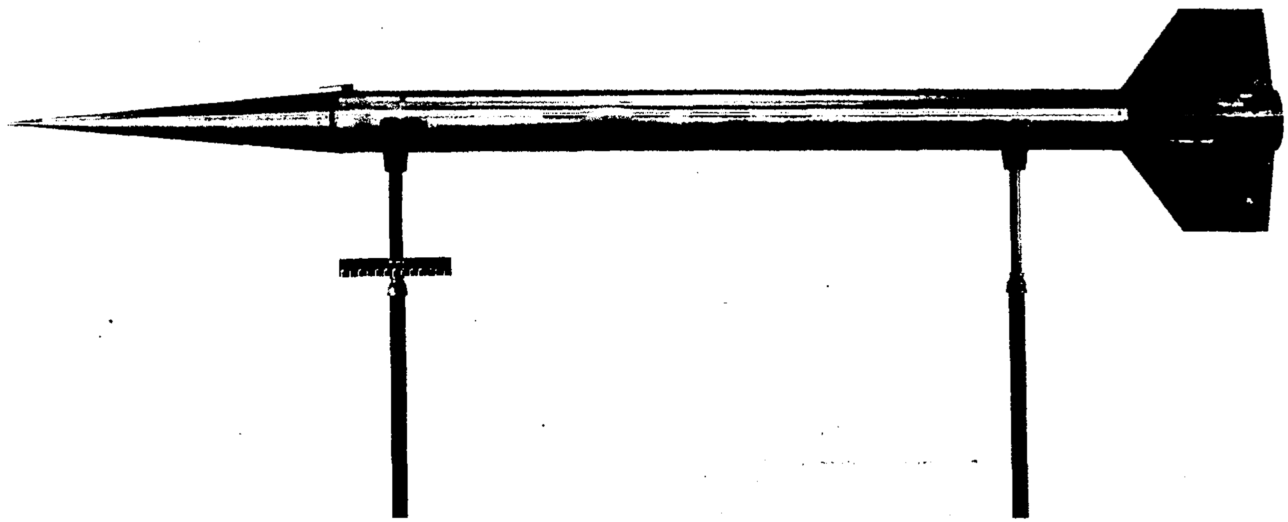


Nose detail



(a) General configuration. Dimensions are in inches.

Figure 3.- Model 2.



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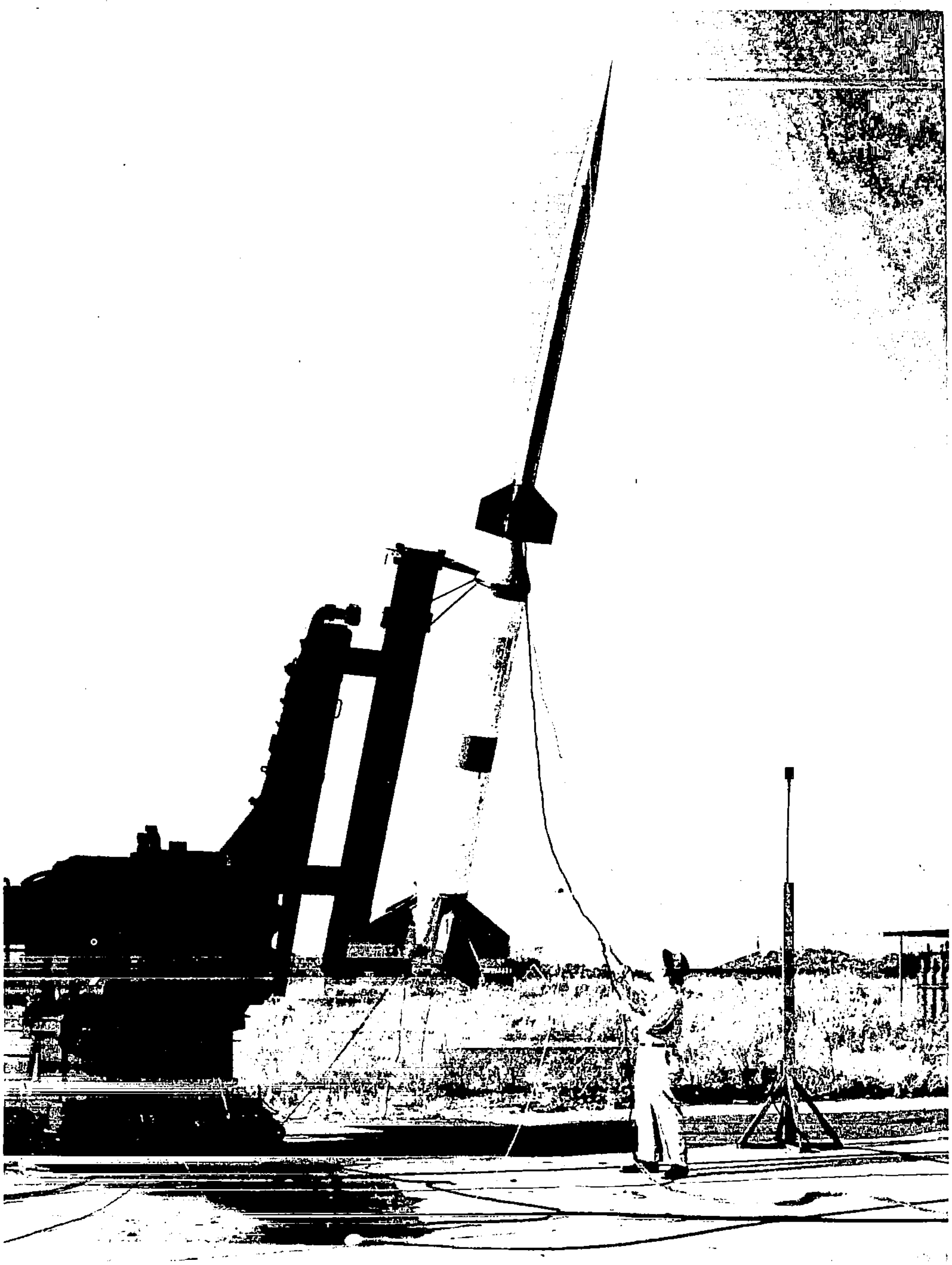
(b) Photograph of model 2.

Figure 3.- Continued.



(c) Model 2 and booster on launcher. L-82478

Figure 3.- Concluded.

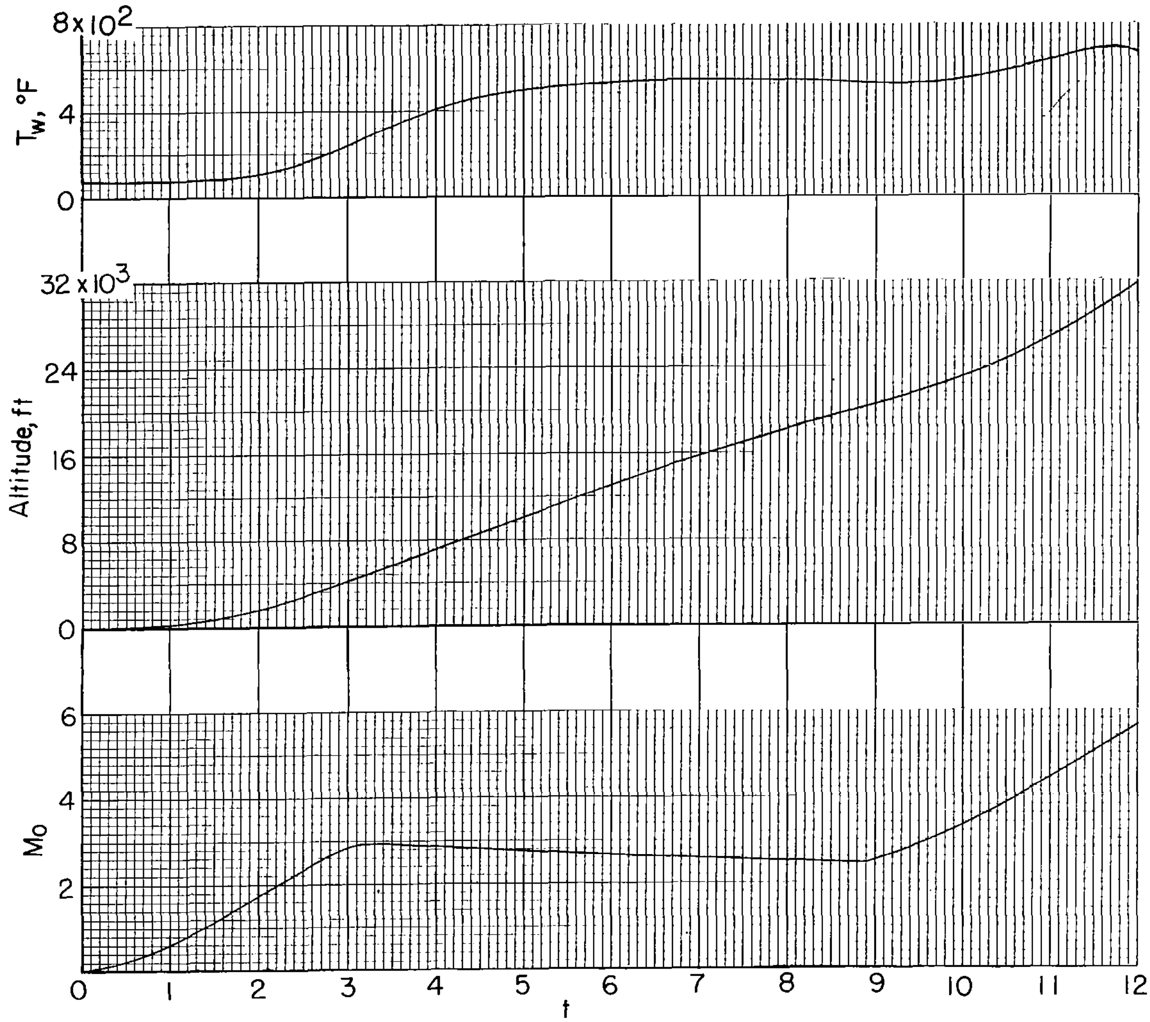


Figure 4.- Time histories of flight conditions for model 2.

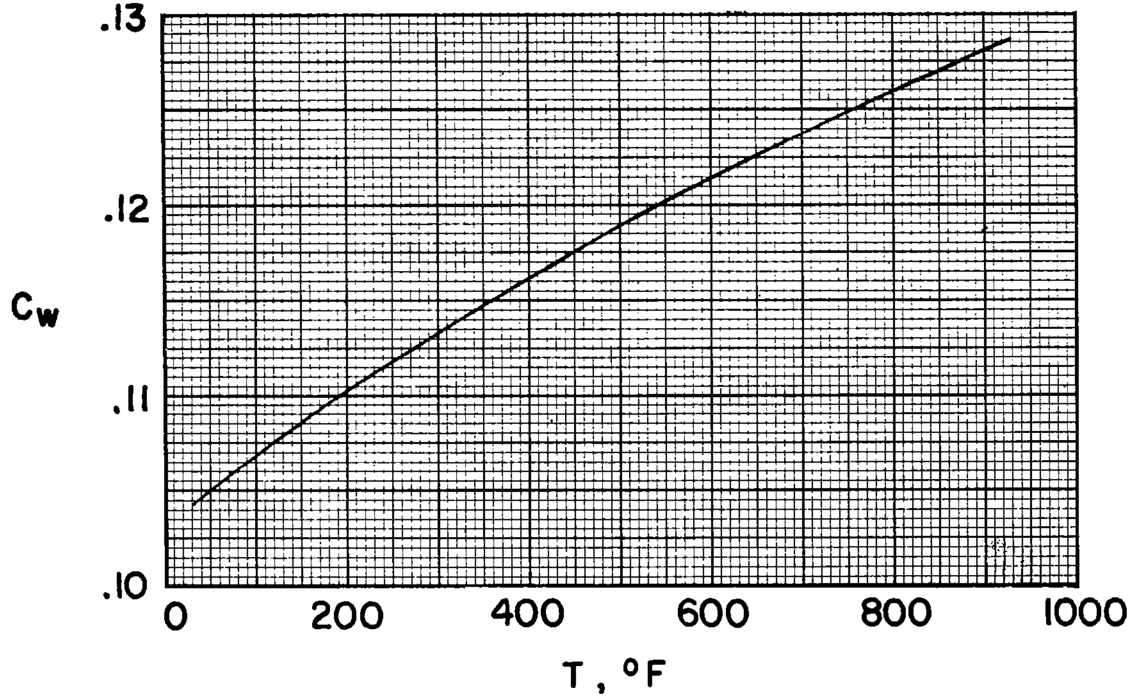


Figure 5.- Variation of specific heat with temperature for annealed Inconel having 0.07 percent carbon content.

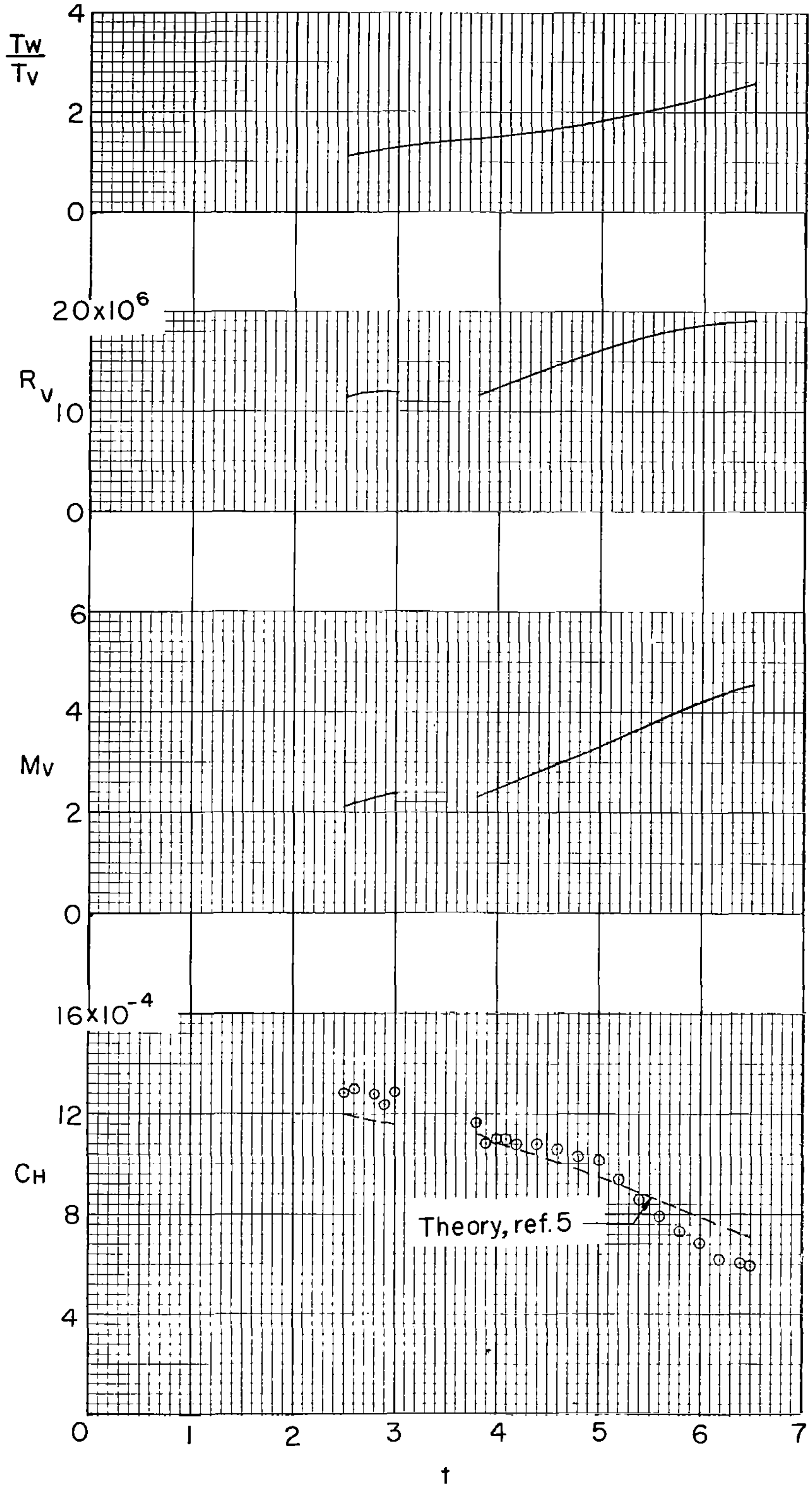


Figure 6.- Time histories of heat-transfer coefficients and controlling parameters for model 1.

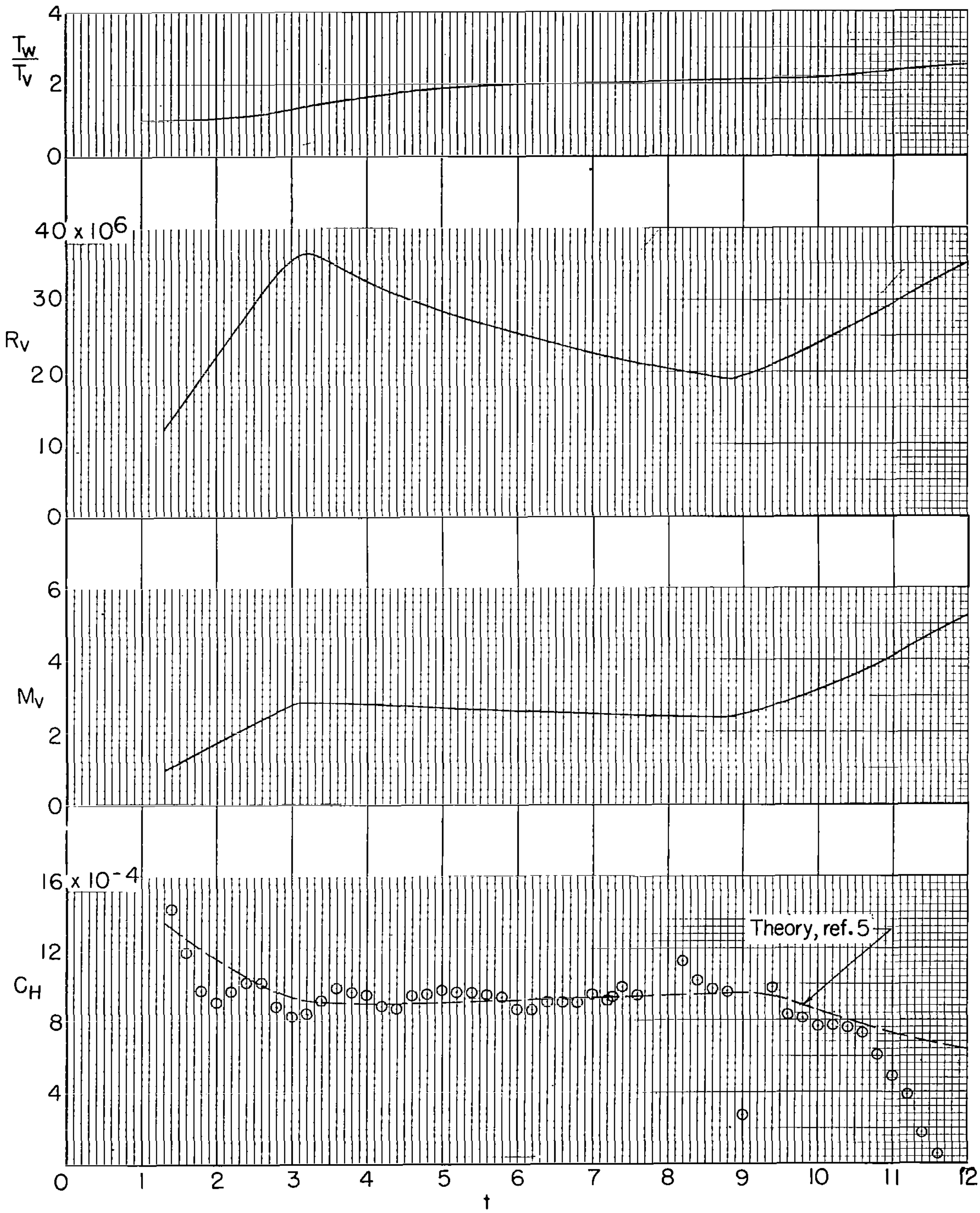


Figure 7.- Time histories of heat-transfer coefficients and controlling parameters for model 2.

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